

# The FALCON concept: multi-object spectroscopy combined with MCAO in near-IR

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**Abstract.** A large fraction of the present-day stellar mass was formed between  $z = 0.5$  and  $z \sim 3$  and our understanding of the formation mechanisms at work at these epochs requires both high *spatial* and high *spectral* resolution: one shall *simultaneously* obtain images of objects with typical sizes as small as 1-2 kpc ( $\sim 0''.1$ ), while achieving 20-50 km/s ( $R \geq 5000$ ) spectral resolution. In addition, the redshift range to be considered implies that most important spectral features are redshifted in the near-infrared. The obvious instrumental solution to adopt in order to tackle the science goal is therefore a combination of multi-object 3D spectrograph with multi-conjugate adaptive optics in large fields. A very promising way to achieve such a technically challenging goal is to relax the conditions of the traditional full adaptive optics correction. A partial, but still competitive correction shall be preferred, over a much wider field of view. This can be done by estimating the turbulent volume from sets of natural guide stars, by optimizing the correction to several and discrete small areas of few *arcsec*<sup>2</sup> selected in a large field (Nasmyth field of 25 arcmin) and by correcting up to the 6th, and eventually, up to the 60<sup>th</sup> Zernike modes. Simulations on real extragalactic fields, show that for most sources ( $> 80\%$ ), the recovered resolution could reach  $0''.15$ - $0''.25$  in the *J* and *H* bands. Detection of point-like objects is improved by factors from 3 to  $\geq 10$ , when compared with an instrument without adaptive correction. The proposed instrument concept, FALCON, is equipped with deployable mini-integral field units (IFUs), achieving spectral resolutions between  $R=5000$  and 20000. Its multiplex capability, combined with high spatial and spectral resolution characteristics, is a natural ground based complement to the next generation of space telescopes. Galaxy formation in the early Universe is certainly a main science driver. We describe here how FALCON shall allow to answer puzzling questions in this area, although the science cases naturally accessible to the instrument concept makes it of interest for most areas of astrophysics.

## 1 Scientific drivers for FALCON

The second generation of instruments for the VLT will certainly be driven by recurrent and still unresolved questions, for which observational answers are

currently at the edge of the possibilities of 8 meter class telescopes. The coming decade, shall be dedicated to the understanding of physical processes involved in known targets from well defined samples of targets. This will require observations of the highest image quality and depth for a limited number of sources.

### 1.1 How and when galaxies formed ?

The deepest past and current galaxy surveys (CFRS, HDF, DEEP) all show that galaxies beyond  $z = 0.5$  were smaller, more irregular and had higher star formation rate than present-day galaxies (Lilly et al, 1998; Hammer et al, 2001). Merging rates were also much higher than today, being proportional to  $(1+z)^4$  (Yee & Ellington, 1995; Le Fèvre et al, 2000). Half of the total light contributing to infrared background has been resolved by ISO (Elbaz et al, 1999). It was found to be dominated by large disks at  $z = 0.5 - 1.2$ , often found in interacting systems (Flores et al, 1999). Accounting for all their UV to IR and radio emission lead to a universal star formation density which declines by a factor between 5 and 10 since  $z = 1$ . A simple integration of the global star formation history shows that half of the present-day stars have been formed since  $z = 1 - 1.5$  (Flores et al, 1999; Madau and Pozzetti, 2000; Madau et al, 2001, Franceschini et al, 2001). At  $z = 3$ , less than a third of the present-day metal content was formed, even accounting for large dust corrections (scenarii with a constant star formation density beyond  $z \sim 1$ ). This is somehow in contradiction with the primordial collapse scenario, where massive galaxies form at much earlier epochs ( $z \geq 3$  or higher). The latter scenario is supported by the apparent non-evolution of the number density of giant ellipticals at  $z = 1$  or higher (Schade et al, 1999; Cimatti, 2001, this proceedings) and by the small dispersion of the fundamental plane for nearby ellipticals. The debate is still open and improved VLT instrumentation shall be developed to study the importance of the evolutionary phase at  $z = 1 - 1.5$ , in a quantitative and systematic way.

The way galaxies are assembling, and how they are re-distributing their mass, velocities and angular momentum, is largely unknown (e.g. Combes, 1999). Cinematics and chemistry of galaxies should be studied over a variety of different redshifts in order (1) to determine how common/important the merging phenomenon is, (2) to map the distribution of disks and spheroids at various times, and (3) to firmly establish the origin of the Hubble sequence. An important redshift range for studying galaxy formation is situated between  $z = 0.5$  and  $z = 2 - 3$ , covering epochs for which most of the present-day stars have been formed. At these redshifts, the important spectral features such as emission lines from [OII]3727 to  $H\alpha$ , and the stellar absorption lines, are observed in the wavelength range  $0.7 < \lambda < 1.9$  microns where ground-based 8-m telescopes are not only competitive with future space telescopes (NGST) but also complementary. Because of the complexity of the mechanisms involved, galaxy formation studies require simultaneously high spatial resolution (down to  $\sim 1$ -2kpc at  $z > 1$ ) and moderate spectral resolution (down to  $\sim 30$  km/s). In other words, 3D spectroscopy is required, with good spatial sampling of the velocity field. This is

achievable by combining 3D spectroscopy with adaptive optics correction over a large field of view.

At higher redshift, very little is known on the formation of the first gravitationally bound structures, namely the first massive proto-galaxies. The answer to the question is intimately related to the universal metal formation history, as most of the present-day metal content is locked into bulges of massive galaxies (Fukugita et al, 1998). In fact, giant elliptical galaxies should be investigated in detail far beyond  $z = 1$  (see Cimatti, 2001, these proceedings): diagnostics from the strong CaII to MgI absorption systems will set constraints on their age and metallicity and will allow for the determination of their stellar content and the epoch of their formation. These lines are redshifted in the near-IR  $I$ ,  $J$  and  $H$ -bands. Detecting the continuum emission is essential to measure absorption lines. The faintness of the continuum emission in distant objects makes such observations very challenging. They require a significant improvement of the image quality and limiting magnitude, coupled with 3D spectroscopy. Alternatively the first epoch of star formation can be dated in massive galaxies hosting a quasar (Dietrich and Hamann, 2001). According to Collin & Joly (2000), heavy element overabundances can not be explained in the context of photoionisation models and are attributed to the presence of a starburst (Hamann & Ferland, 1993). At high redshifts ( $z = 4.5$ ), quasars' line ratios (MgII/FeII) indicate solar and supersolar metallicities of the gas, which could be related to SN Ia metal production. Given an evolutionary time scale of  $\sim 1$  Gy for the progenitor stars of SN Ia, this leads to substantial star formation up to  $z = 8$ . Very first events of star formation at  $z = 10 - 20$  can be probed from deep spectra of  $z = 6$  QSOs (see Fan et al, 2001), for which the FeII lines ( $< 3200 \text{\AA}$  at rest) are redshifted in the  $J$  and  $H$ -bands. Improvements of image quality and moderately high resolution are crucial for programs aimed at probing bulges of distant galaxies, hence small, faint objects.

## 1.2 Stellar physics: a clue to open questions in cosmology

Type Ia supernovae are the best extragalactic standard candles known so far. The Hubble diagram established from  $z = 0.5$  to  $z = 0.83$  has already shown that cosmologies with non-zero cosmological constant ( $\Lambda > 0$ ) are favored by the observations (Perlmutter et al, 1998). However, the value of the cosmological constant has little effect on the Hubble diagram at low redshift, given the accuracy of present-day observations. This surprising result by Perlmutter et al. therefore needs to be extended at higher redshift, where the detailed predictions of  $\Lambda$  cosmologies can be compared with the data. The most recent discovery places the highest redshift supernova at  $z = 1.7$  (Riess et al. 2001), but due to the faintness of the target, there is no spectroscopic confirmation of its redshift. Spectroscopic follow-up is essential in this field, whether it be to provide redshift information or to derive physical parameters of the supernova. At  $z > 1$ , most spectral features relevant to the study of supernovae are redshifted in  $J$  and  $H$ -bands. Obtaining very deep spectra is at the edge of the possibility for 8

meter class telescopes. Pushing further their spectroscopic limits, even by only 1 magnitude would place the present and future results on a firmer ground and settle the issue of the value of the cosmological constant. Fainter point source detection is one of the primary goal of the FALCON concept.

Red supergiants are present in populations with ages between about  $10^7$  and about  $10^8$  yrs. Their predicted colour and luminosity distributions are very sensitive functions of age and metallicity during that time. Obtaining proper colour-magnitude distributions of red giants is a promising way for the determination of the recent history of starburst and young post-starburst galaxies. AGB stars are dominant sources of near-IR light at post-starburst ages of  $10^8$  to about  $2 \cdot 10^9$  yrs. The distribution of carbon stars among these traces the intermediate age star formation history and carbon star proportions indicate metallicity. Theoretical spectra for luminous cool giants suggest that metallicity has a very strong effect on the spectra. The systematic studies on near-IR metal lines in globular cluster red giants by Frogel et al. (1999) promises that it will become possible to estimate metallicities from  $H$  or  $K$ -band spectra ( $R=5000$ - $10000$ ) even from very late type spectra. Once these calibrations are obtained and extended to RSG and AGB stars, detailed diagnostics will be available for the post-starburst galaxies and massive intermediate age clusters that FALCON shall observe spectroscopically out to  $\sim 100$  Mpc. These studies have direct repercussions on distant galaxies studies, because the calibration of the stellar mass is far from being accurately established.

## 2 Proposed specifications for a 2nd generation spectrograph at VLT

**Going deep: more object, less sky.** The S/N performances are limited by the light concentration entering a spatial element of the spectrograph. For star-like sources the S/N is directly proportional to  $FWHM^{-2}$ . For more extended faint sources the key issue is to minimize the ratio of the sky to object light which enters the spectrograph. Since most of the distant galaxies ( $z > 0.5$ ) have half light radius  $r_{05}$  in the range  $0''.15$  to  $0''.5$ , it is crucial to sample about one tenth of an arcsecond, i.e. 1-2 kpc, the size of a large star forming region. Adaptive optics coupled with spectroscopy is the ideal way to reach this goal.

Only 3 D spectroscopy can address the question of galaxy dynamics, including the interacting systems and galactic disks. Spectroscopy using integral field units with a total aperture adapted to distant galaxy sizes will, in one shot map the whole velocity field: a goal out of reach of the traditional slit spectroscopy.

Going deep implies improving the overall throughput of the instrument. It also implies that efforts should be put on limiting the sky signal to the strict minimum. OH suppression techniques, whether they be under the form of filtering or numerical techniques, requires a spectral resolution  $R \geq 5000$ . Since the velocity

dispersion of most distant galaxies spans over the range 20-100 km/s, the spectral resolution should in fact exceed this and reach values around  $R = 15000$ , which is also adequate for studies of abundances in stars.

**A wide field and multiplex capability.** A large field of view for selecting targets in a multi-IFU mode is a prerequisite. This would optimize the efficiency of follow up observations of surveys carried out at other wavelengths over a large field of view, e.g., the sources provided by XMM, SIRTf or HERSCHEL. The number density of high- $z$  galaxies bright enough to be observed in 3D spectroscopic mode is relatively small. For example the number density of starburst galaxies detected by ISO at  $z \geq 0.5$  is less than 50 per 100  $arcmin^2$  and only a fifth of them would have enough flux in their emission lines to allow for a 3D spectroscopic analysis of their velocity fields. Stellar fields in Local group galaxies require very large fields of view. Keeping a field of view close to that of the Nasmyth ( $\Phi = 25$  arcmin) of the VLT units is therefore capital.

**High spectral resolution: going for emission lines.** A spectral range extending to the near-IR would allow to take full advantage of the adaptive optics technics and to observe always in sub-tenth-arcsec seeing. The 0.7-1.8  $\mu m$  domain includes most of the important spectral features for galaxies at  $z = 0.5 - 2$ . Optimal targets for dynamical studies of galaxies (3D spectroscopy) are limited with an 8 meter telescope, to  $\sim I_{AB} = 23.5$  (or  $H_{AB} = 22$  for an Scd energy distribution) galaxies. Most of these galaxies have redshifts in the range  $z = 0.5 - 2.5$ , with a peak at  $z \sim 1.5$ . Their gas velocity field can be mapped using the  $H\alpha$  line up to  $z = 1.5$  and up to  $z = 2.5$  or more using the [OII]3727,  $H\beta$  and [OIII]5007 lines.

### 3 The FALCON concept and expected performances

A major limitation to traditional adaptive optics is the very small field of view inherent to the isoplanatic patch size. While this is no serious problem for detailed studies of individual sources, it is a killer as soon as the aim is to survey large number of objects, or to follow up sources detected at other wavelengths on a wide field of view. It has been demonstrated (Gendron et al, 2001, in preparation) that, by relaxing several conditions of the adaptive optics, one could significantly improve image quality in the near-IR, while providing corrections for a large number of objects in wide (cosmological) fields. This can be done by:

- restricting the adaptive optics correction to  $0''.15 - 0''.25$  FWHM
- optimizing the correction to several small areas of few  $arcsec^2$  each, and selected within a large field (for example a Nasmyth field,  $\Phi = 25$  arcmin).
- using 3 reference stars ( $R \leq 16$ ) per small area (or target) for a multi-analysis of the wavefront (MCAO technics).
- considering low (3 to 5 Zernike modes) to moderately high ( $\geq 60$  Zernike modes) order compensations.



**Fig. 1.** Seven examples of uncorrected stellar sources at locations randomly selected in a cosmological field; (*Bottom*): same sources after MCAO correction with optimization at source location (three reference stars) assuming a correction up to the 15<sup>th</sup> Zernike order.

Simulations have been performed assuming three turbulent layers at 0km, 1km and 10km, with phase variance of 20%, 60% and 20% respectively, and a resulting seeing of 0".65 at 5500Å . 500 galaxies have been randomly selected within five  $\Phi=25'$  cosmological fields ( $b^{II} \geq 45$  degrees), and the phase has been estimated from a MCAO system simulator developed by Fusco (2000), assuming a Shack-Hartmann sensor type and a S/N of 10 which roughly corresponds to  $R \leq 16$  reference stars. Figure 1 displays how the image quality is improved at different object locations. Figure 2 probes that large gains in S/N can be obtained ( $\sim 1$  mag at  $1.6\mu\text{m}$ ) by correcting only the 5 first Zernike modes (including tip-tilt and defocus). Obtaining a significant further gain would requires higher order compensations up to 60 Zernike modes, but a gain by 1 mag already allow to fulfill many proposed science drivers.

The basic concept of FALCON (Sayède et al, 2001, in preparation) includes small miniaturized devices, called "adaptive buttons", located on the beam entering the IFUs across the Nasmyth field. Similar buttons will be used on objects and reference stars, and allow for correction of the wave-front. The development of FALCON (*Fiber-spectrograph with Adaptive-optics on Large-fields to Correct at Optical and Near-infrared*) will be done in two stages:

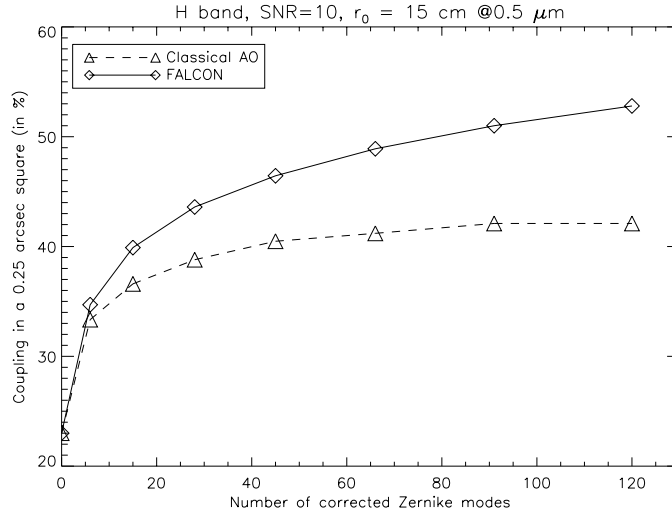
1. tip-tilt and defocus with a five motorized axis lens (Figure 3)
2. correction of higher order modes with a micro deformable mirror

Only a limited number of reference stars is required in the first stage (1 star for most of the targets, see Figure 2), and for such a limited correction, the system could work either in open loop or in partially closed loop. Although far superior to any existing instrument by its image quality, it would be similar by many aspects to GIRAFFE at VLT. GIRAFFE will provide the first system of deployable multi-IFUs (20 IFUs, Figure 4) available at the focus of a very large telescope.

Several developments are underway for optimizing the correction system (measurements and actuation), and the control loop. Further investigations are

required to adapt the fiber system to FALCON (including microlenses,  $\sim 50\mu\text{m}$  diameter IR fibers, limitation of the focal ratio degradation losses). The second stage is more ambitious and would highly benefit of the former feasibility study. The goal is to add a micro deformable mirror (MDM) to the compact adaptive button in order to correct higher order Zernike modes (Figure 2), requiring a relatively high actuator density. The main advantages of MDMs are their compactness, scalability, and specific task customization using elementary building blocks, including on-board electronics. Four such adaptive buttons will be needed for each target, including 3 on the reference stars, for which a close loop correction is needed. The whole system would eventually work in a partially closed loop mode, under the control of the MCAO software and taking advantage of the similarity between the 4 devices (study in progress). The resulting instrument will eventually produce an image quality competitive with that of NGST spectrographs.

Assuming the completion of the first stage (only low order correction), FALCON would provide a S/N gain of up to 1 magnitude for a stellar source, when compared with an instrument without adaptive correction. For compact sources with unresolved lines -such as the numerous HII regions in distant galaxies, there will be an additional gain following  $S/N \sim EW/\lambda \times R$ , totalizing 2-3 magnitudes improvement in S/N if compared to  $R=2000$  spectrographs, just because the fraction of spectra accessible “between” the sky lines is much larger. For example, at  $R=10000$ , FALCON would beat NGST at scrutinizing the properties of  $\sigma=$



**Fig. 2.** Average fraction of light entering a  $0''.25$  square aperture after MCAO correction as a function of the number of corrected Zernike modes. Sources have been assumed to be stellar and the correction was done at  $1.6\mu\text{m}$

**Fig. 3.** JPEG Files , Example of an adaptive button for correcting 5 Zernike modes (concept by F. Sayède and F. Rigaud). The lens-doublet L2 is in the pupil plane and L3 is a field lens. Microlenses in the image plane of the button provide a spatial sampling of the source and adapt the light injection in the optical fibers.

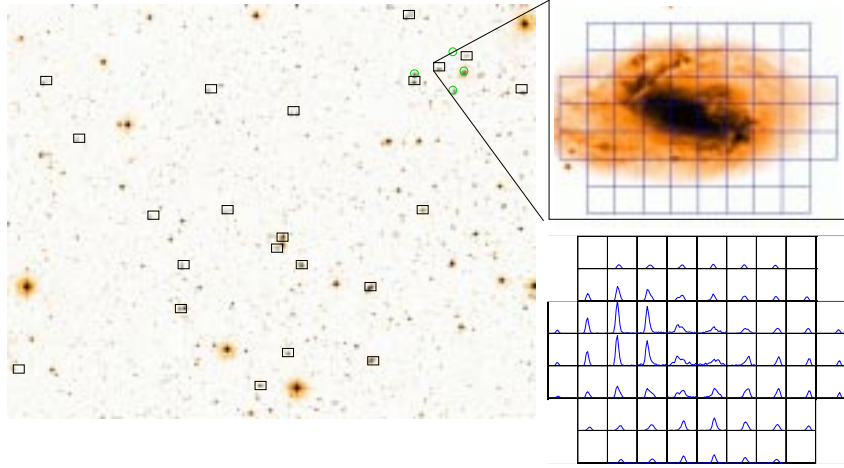
**Fig. 4.** JPEG File, Face-on view of one of the 20 GIRAFFE deployable IFUs (realisation by L. Jocou and I. Guinouard, see also Jocou et al, 2000) with 20 microlenses (size= $140\mu\text{m}$ ) adapted on the prism; performances ( $\sim 60\%$ ) could be improved for FALCON by minimizing the focal ratio degradation losses.

30km/s HII regions at very large distances. A simple simulator of FALCON, assumed to be mounted at VLT, shows that for a  $L^*$  galaxy at  $z = 1.5$  ( $I_{AB}=23.5$  and  $H_{AB}= 22$  for a Scd spectral type), the S/N per spectral resolution element ( $R=5000$ ) at  $1.6\mu\text{m}$  would be  $4.5\pm 1$  with a total exposure time of 2 hours. This number is boosted to 130 for a  $\text{EW}=60\text{\AA}$   $H\alpha$  line, and studies of the velocity field map could be done in great details (Figure 5). FALCON would be unique for spectroscopy of supernovae at  $z = 1.5$ : if we assume  $J_{AB}=25$  after an extrapolation from SN 1997ap at  $z=0.83$  (Perlmutter et al, 1998), a  $S/N=5\pm 2$  ( $R=600$ ) would be reached after 6 hour exposures.

## 4 Summary

We propose a new concept for developing spectroscopic studies with 8 meter ground based telescopes. FALCON would allow adaptive corrections for many targets in large fields of view and would achieve significant improvement of the image quality or light concentration for more than 80% of the cosmological sources. A realistic design would be 60 deployable IFUs (Figure 5) within a  $\Phi= 25$  arcmin field, providing  $60 \times 62 = 3720$  spectra covering ( $R=5000$ ) the  $I$ ,  $Z$ ,  $J$  or  $H$ -bands. Spectral resolutions would range from  $R=5000$  (required for a proper removal of strong OH lines) to  $R=20000$  (for stellar studies). The first stage of development for FALCON is to correct five of the six Zernike modes (tip-tilt, defocus and 2 astigmatisms) with a lens, providing a 1 magnitude gain in S/N for a stellar source. The second stage is aiming at correcting higher order modes with a micro deformable mirror, hence providing a supplementary gain of 1 magnitude. FALCON could be implemented at the OzPoz at UT2 (Kueyen). Offering 3D spectroscopy and medium resolving power, it will be the natural complement of NGST for dynamical studies of distant galaxies, for follow-up studies of XMM, SIRTf and PLANCK sources, for abundance surveys of cold stars within and beyond the Local Group and for massive spectroscopic studies of stellar populations in general.





**Fig. 5.** Several IFUs (squares) in a  $\Phi = 25$  arcmin field; 3 reference stars are shown (circles) for one of them; a zoom in the upper right shows an individual IFU made with  $62 \times 0''.12$  square microlenses laid on a  $z = 1.48$   $I_{AB} = 23.5$  galaxy; on the bottom right the corresponding spectra around the  $\text{EW} = 60 \text{ \AA}$   $H\alpha$  line is presented, revealing the presence of an HII region on the left of the galaxy, as well as resolving its velocity field

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